SRF photoemission electron guns at BNL: First commissioning results

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Introduction

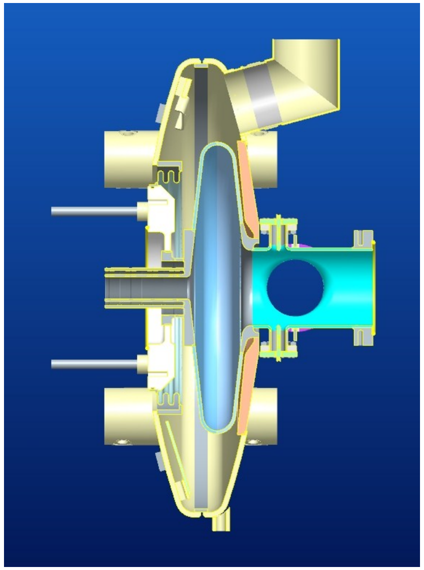
Two SRF photoemission electron guns are under commissioning at BNL:

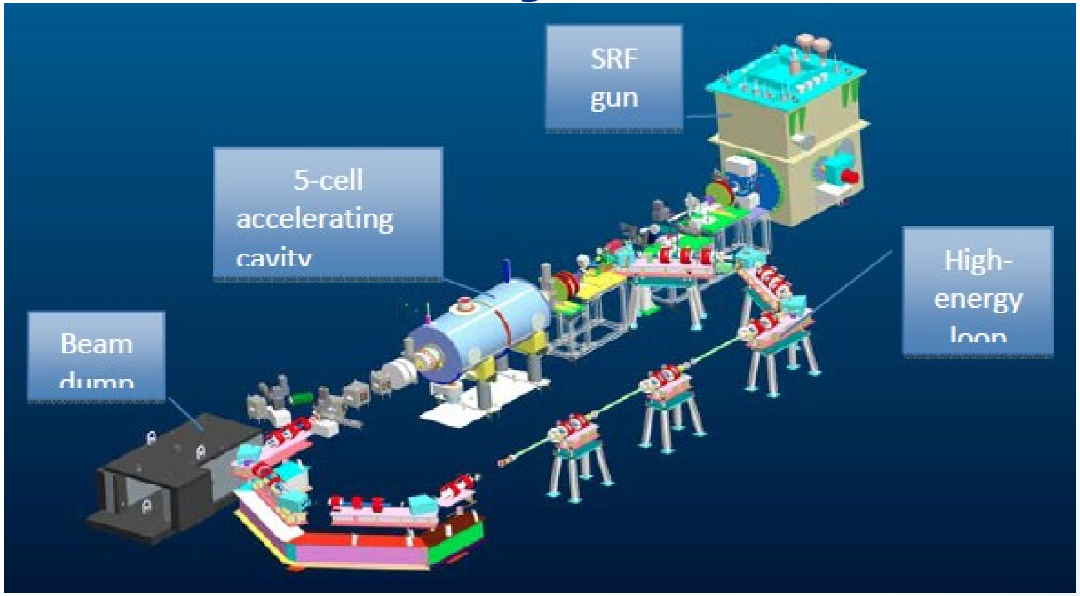
- A 704 MHz ½-cell elliptical gun to deliver high bunch charge and high average current beams for the R&D ERL facility.
- A 112 MHz QWR gun to produce high bunch charges, but low average beam currents for the Coherent electron Cooling Proof-of-Principle experiment.

In this talk I will describe main design features of the two SRF guns, present recent test results and discuss our plans.

Posters: MOP016, MOP027, MOP028

R&D ERL facility

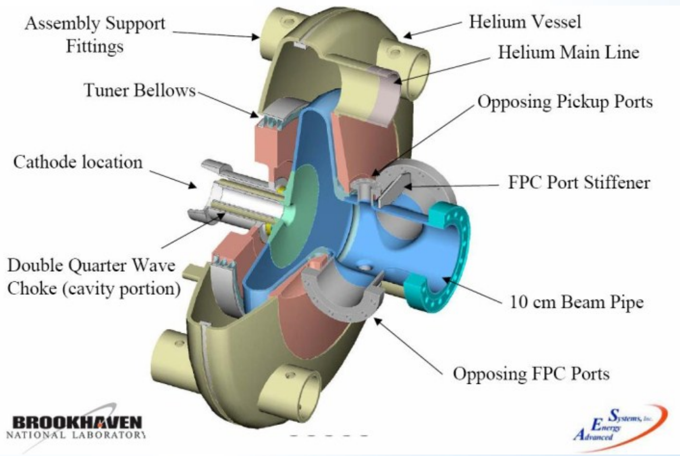




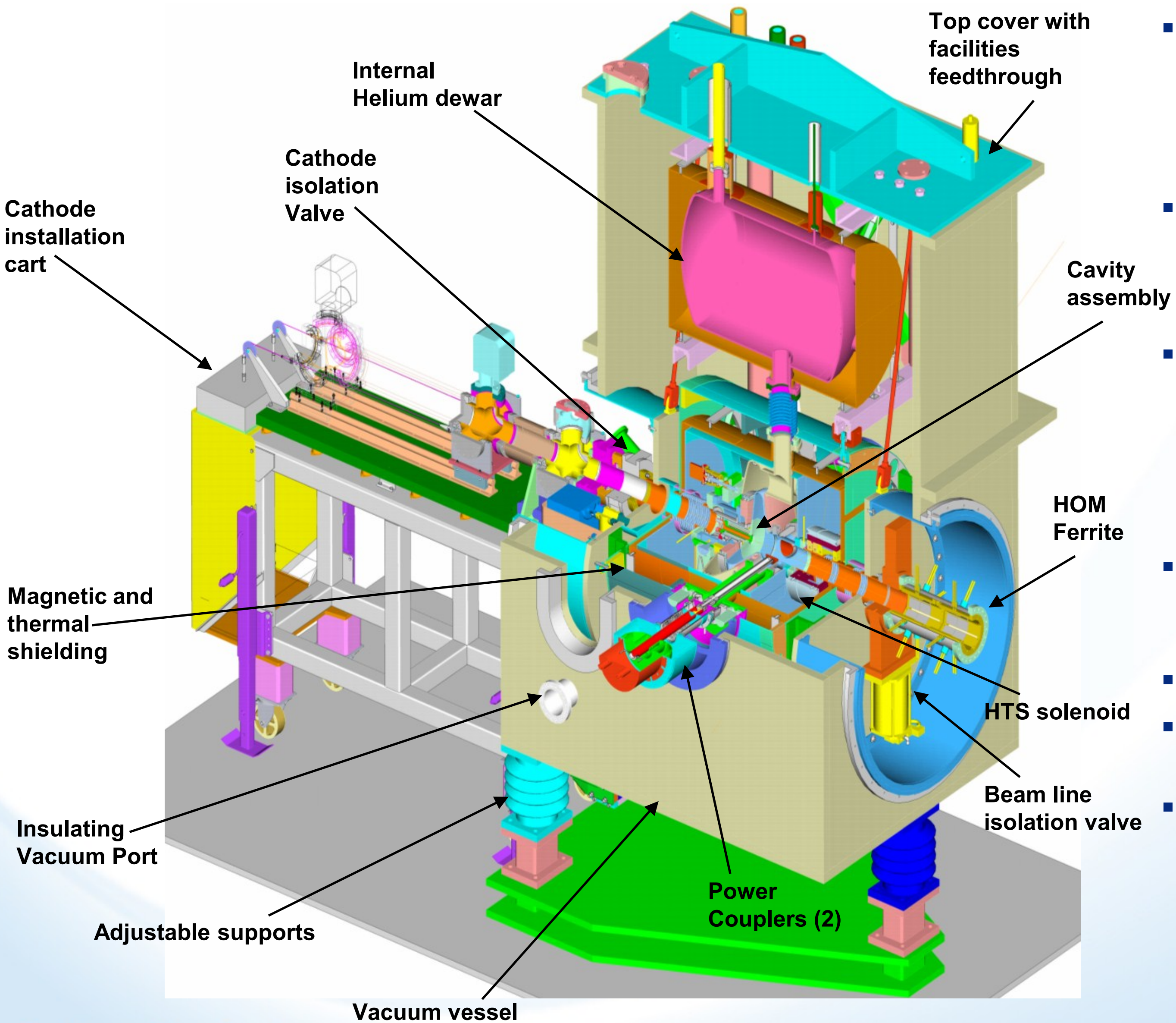
- A prototype ERL (R&D ERL) will demonstrate parameters of the electron beam required for high energy electron cooling and for electron-ion colliers. This facility will serve as a test-bed for new range of beam parameters whose application will extend well beyond the goals set forward by Collider Accelerator Department at BNL.
- The 5-cell cavity is operational and ready for beam.
- The SRF gun is in the commissioning stage.
- An injection merger is being installed to test the concept of emittance preservation in a beam merger.
- Then the recirculation loop will be completed to demonstrate energy recovery with high charge per bunch and high beam current.

704 MHz SRF gun system parameters

RF frequency	703.5 MHz
Cavity active length	8.5 cm (0.4 cell)
Maximum energy gain	2.5 MeV
Maximum field at the cathode	33.4 MV/m
E_{acc} at 2.5 MV	29.4 MV/m
e^- emission RF phase at 2.5 MV	33.4°
Energy gain at 500 mA	2.0 MeV
e^- emission RF phase at 2.0 MV	29.9°
Beam power at 500 mA	1 MW
R/Q	96.2 Ohm
Cavity geometry factor	112.7 Ohm
Cavity Q_0 at 2 K	3×10^{10}
Cavity operating temperature	2 K
Cavity RF losses (2 K) at 2.0 MV	1.4 W
Cathode operating temperature	80 K
Copper cathode RF losses (80 K) at 2.0 MV	226 W

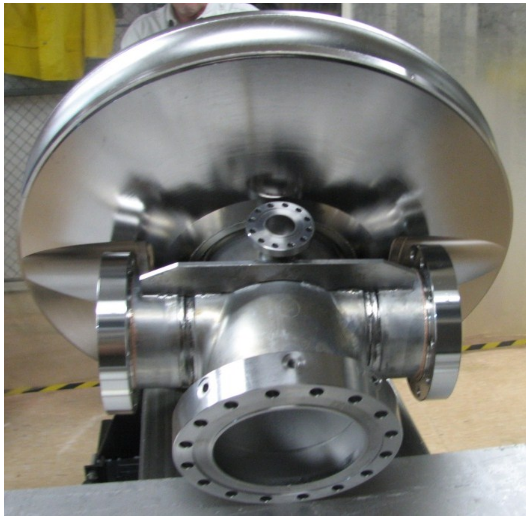


SRF gun cryomodule

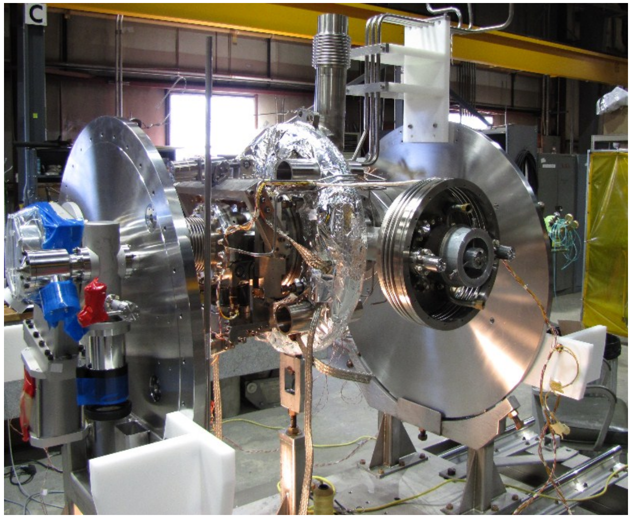


- The 703.75 MHz ½-cell SRF gun with an independently cooled (by LN_2) demountable cathode stalk will use a multi-alkali (CsK_2Sb or possibly NaK_2Sb) photocathode.
- A quarter wave RF choke-joint supports the photocathode stalk and has triangular grooves for suppression of multipacting.
- Two Fundamental input Power Couplers (FPCs) will allow delivery of 1 MW of RF power to a 0.5 A electron beam at an energy gain of 2 MeV. The couplers were conditioned off line in 2012.
- A high-temperature superconducting solenoid is located inside the cryomodule.
- The cavity active length is 8.5 cm.
- Frequency tuning range is 1.2 MHz (1 mm of cavity deformation).
- HOM damping is provided by an external beamline ferrite load with a ceramic break.

SRF gun cryomodule (2)



704 MHz gun cavity

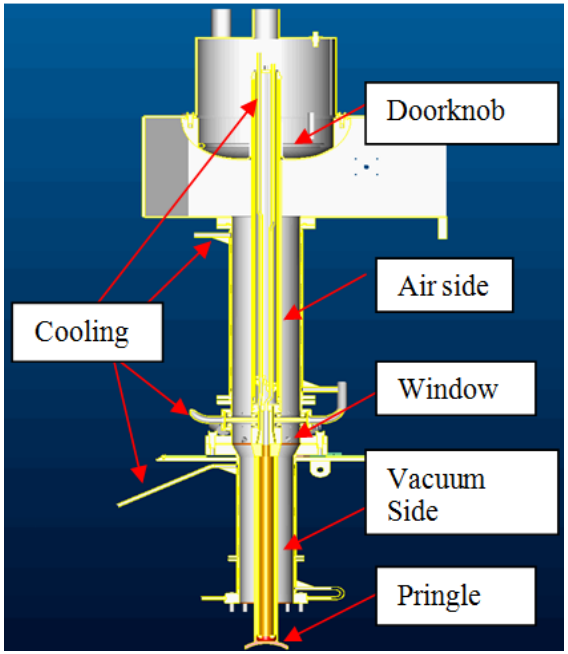


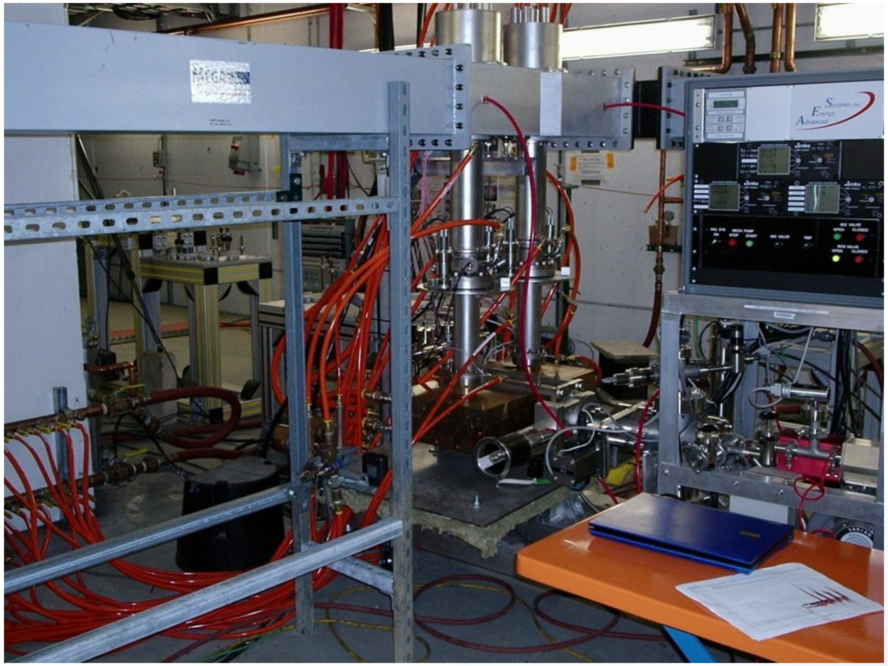
SRF gun cold mass

Assembled SRF gun cryomodule

- 704 MHz ½-cell SRF cavity was vertical tested at JLab in 2009.
- The cryomodule was designed and fabricated by AES, assembly was done at BNL.
- The cathode deposition chamber, transport and insertion mechanism are ready.
- SRF gun commissioning started in Nov. 2012.

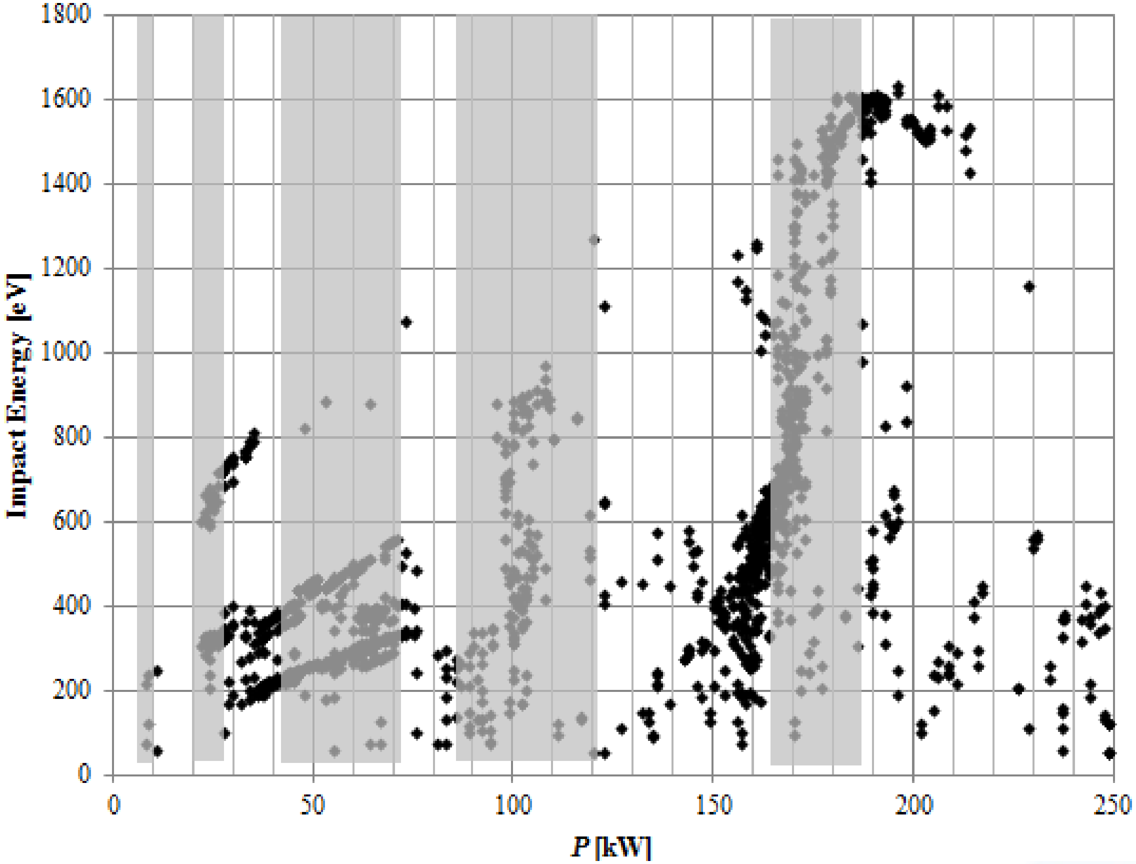
High power fundamental RF coupler

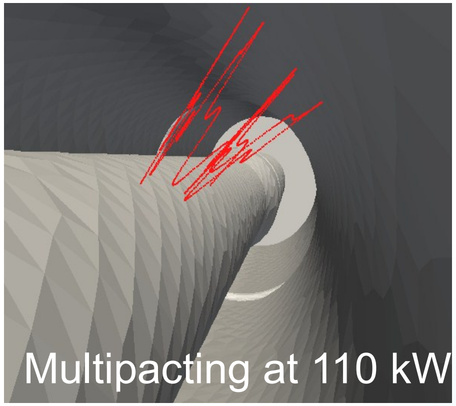


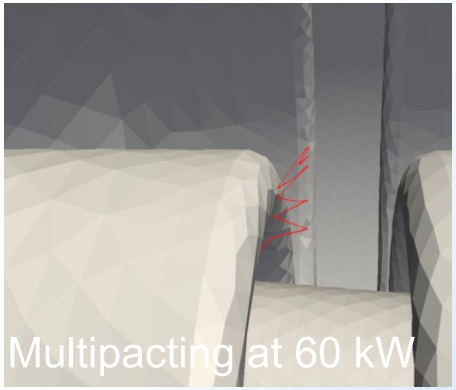


- The couplers were designed for a 1 MW transmitted power. Water cooling for the BeO window ensures that the temperature rise stays below 0.1° C.
- Pringle tip at the inner conductor lowers the Qext into the range between 40,000 and 70,000.
- Water cooling for the inner conductor and air side; 5 K helium gas cooling at the vacuum side outer conductor.
- Prior to installation of the FPCs, they were conditioned with 1 MW klystron. RF power was limited to 125 kW in CW mode to keep local field levels at standing wave maximum the same as they would be at 500 kW. RF power in pulse mode was up to 250 kW (limited by the klystron collector).

Comparison of MP simulations and test

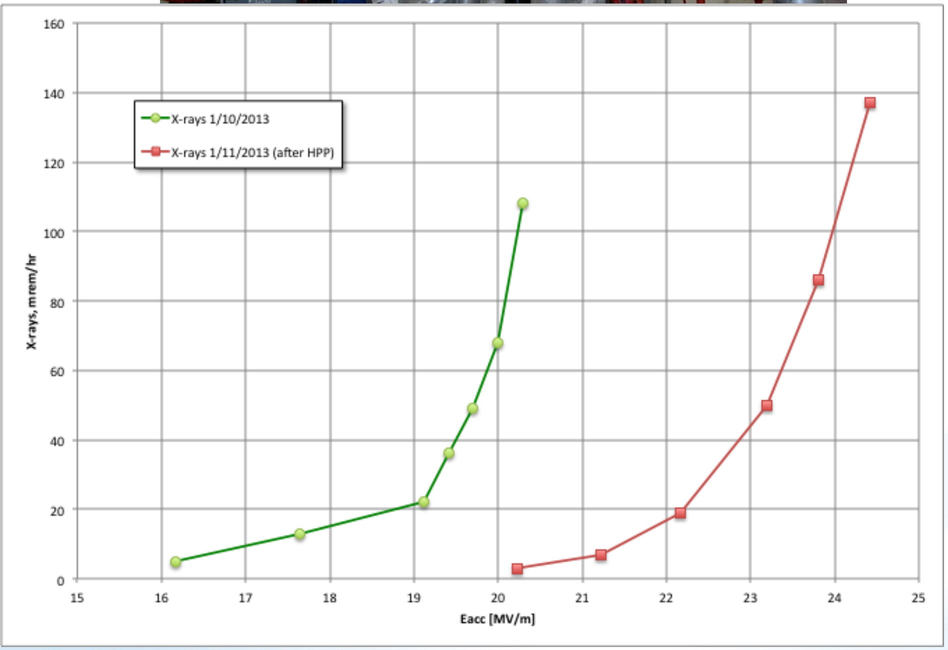






- ACE3P code was used to simulate the electron behavior trajectories, the simulations were carried out for the FPC conditioning setup.
- Simulations show multipacting at the RF power levels of about 8 to 10 kW, 16 to 25 kW, 40 to 70 kW, 85 to 120 kW and about 165 to 185 kW. All these zones were observed in the experiments
- The simulations also show that multipacting zones are not sensitive to frequency. However, the strength of multipacting changes with frequency.

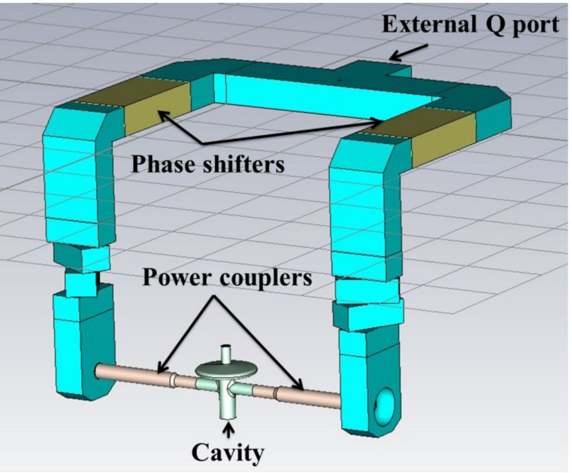
704 MHz gun commissioning w/o a cathode insert **Poster: MOP027**

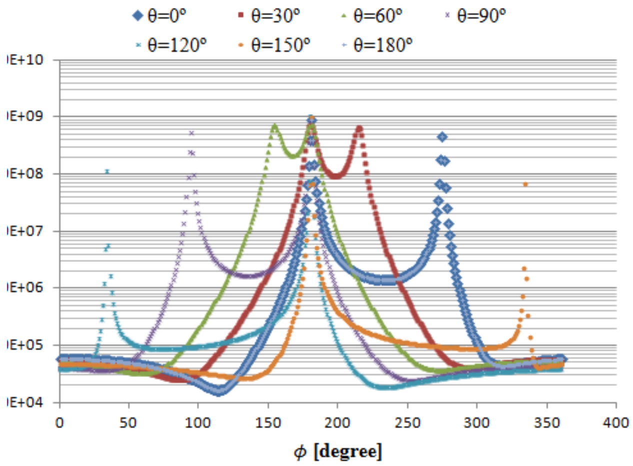


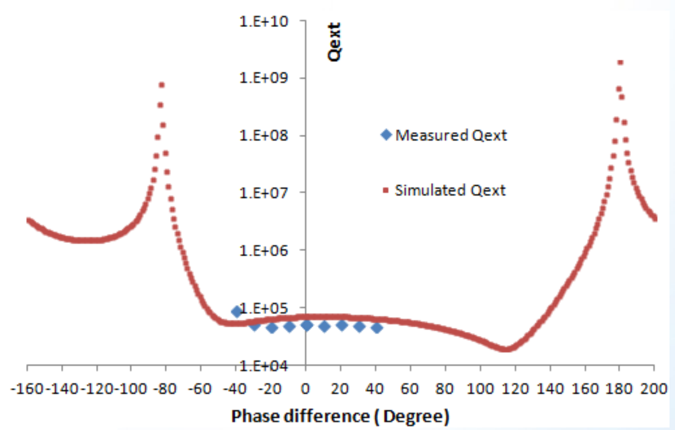
- The gun cryomodule was assembled last year and is installed in the ERL block house. Its 1 MW CW klystron, cryogenic system and other ancillary systems are fully operational.
- The initial commissioning of the gun without a cathode is complete (Nov. 2012 to Mar. 2013) with the gun cavity achieving 2 MV (the original design voltage) and 220 kW of RF power in CW mode.
- In pulsed mode, with a 0.7 ms pulse duration and 1 Hz repetition rate, the RF power was up to 400 kW. This allowed high-power RF processing of field emission in the cavity.
- Digital LLRF was commissioned. So far we demonstrated the cavity field amplitude stability of 2.3e-4 and phase stability of 0.035° (both rms).
- Measured LF detuning coefficient is -11.9 Hz/(MV/m)^2, the cavity frequency sensitivity to He bath pressure is 704 Hz/Torr.

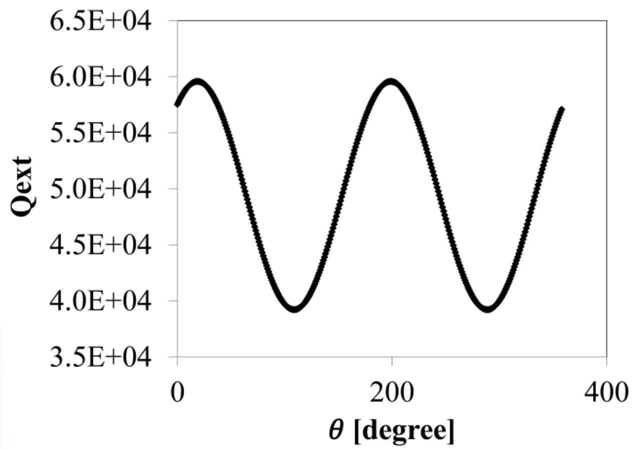
Qext adjustment with phase shifters

Poster: MOP028



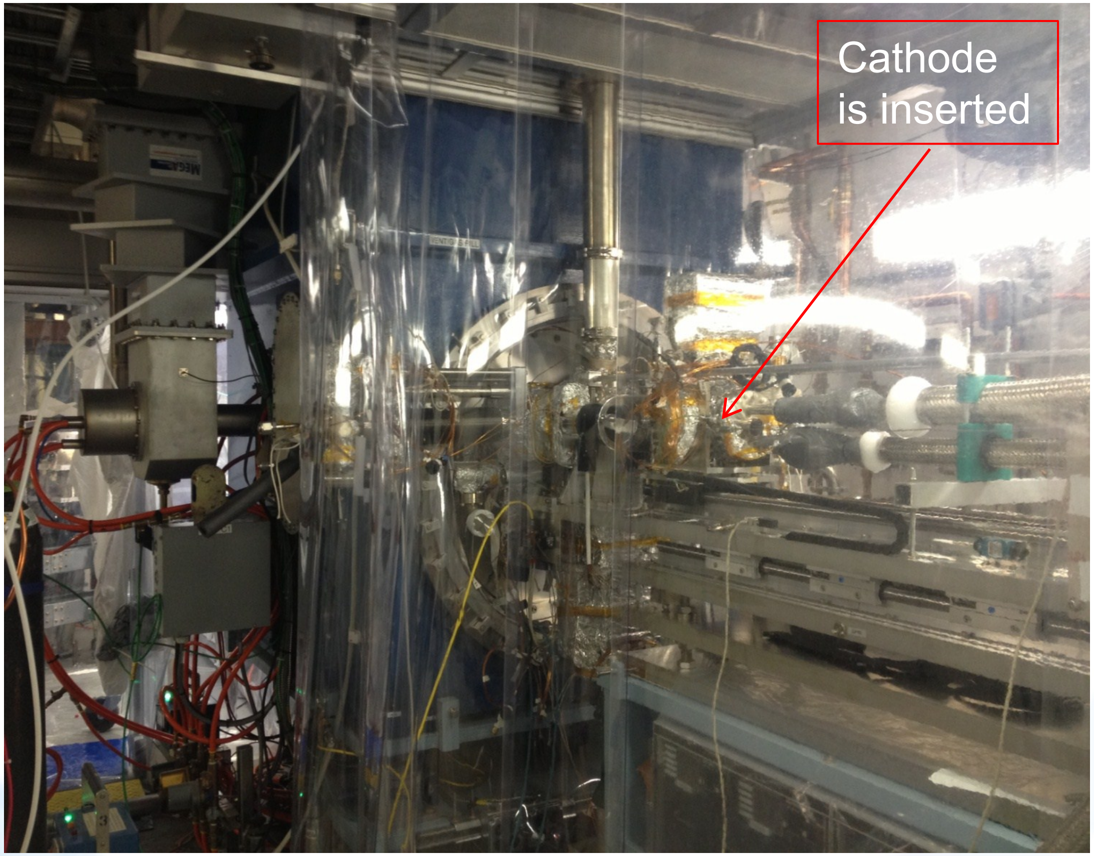






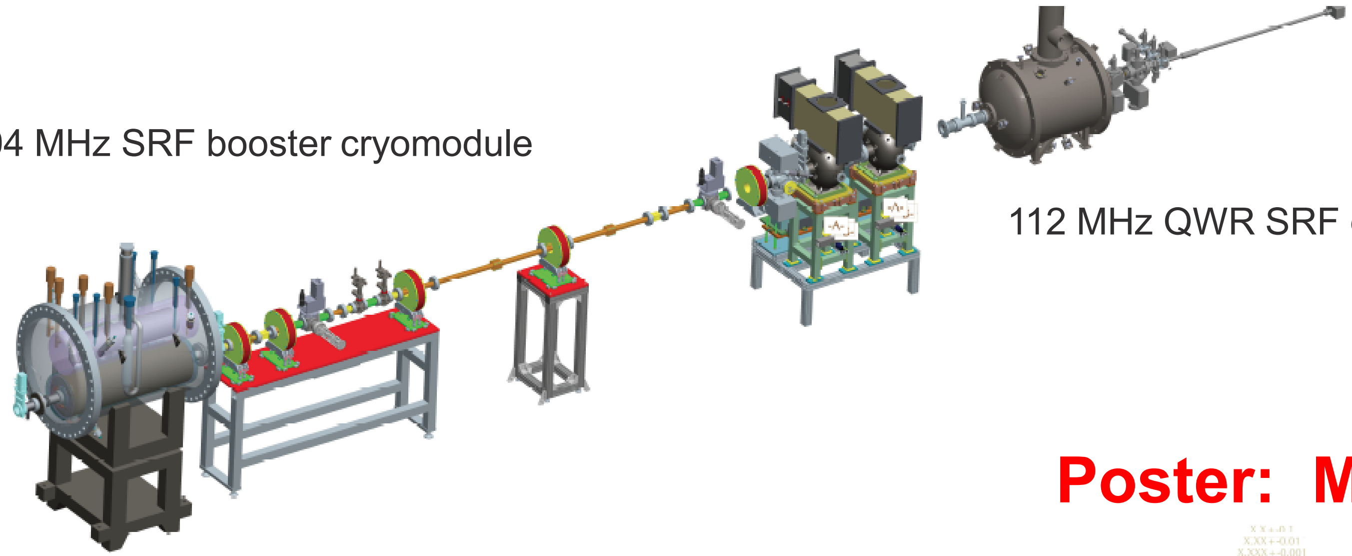
- We use a shunt T to split RF power equally between two waveguide arms.
- The phase difference between the two arms affects the external *Q* value.
- Simulation results show that there are always two external *Q* factor peaks within one period (360°). One peak is fixed at 180° for all conditions and the other one would move with periodically with period of 180°.
- When both phase shifters are adjusted simultaneously, *Q* periodically changes with a period of 180°. This would allow adjustment of ±20%
- When both phase are at 0°, the Q_{ext} factor of the system is measured as 5.75×10^4. The phase shifter in each arm is only able to shift the phase by 40°.
- Measured Q_{ext} versus phase shift in the actual ERL SRF gun setup is compared with simulations . Measurements were carried out at both high power (via LLRF) and low power with network analyzer, producing the same results.

704 MHz gun commissioning with copper cathode stalk **Poster: MOP027**



- The SRF gun is now under commissioning with a copper cathode stalk (from Aug. 2013).
- So far, we have reached 1.8 MV with an RF pulse duration of 40 ms; 2.2 MV at 500 us. The pulse repetition was 10 Hz in both cases.
- At low field levels there was MP in the choke-joint. At higher fields – FPC re-conditioning.
- The conditioning will continue until we reach stable operation at 2 MV in CW.
- The test with a real multi-alkali cathode and beam is tentatively scheduled for Oct. - Nov. 2013.

Coherent electron Cooling Proof-of-Principle experiment



Poster: MOP016

- A Proof-of-Principle (PoP) experiment is under preparation at BNL to demonstrate feasibility of CeC for future improvements of luminosity in high-energy hadron-hadron and electron-hadron colliders.
- Only one RHIC ion bunch will be cooled. To generate a high-bunch-charge, low-repetition-rate beam, we are building a short 22-MeV superconducting linac.
- The linac includes two SRF systems: a 112-MHz Quarter Wave Resonator (QWR) photoemission electron gun and a 704-MHz booster cavity cryomodule. In this paper we describe the two SRF systems, report on the project status and test results, and discuss plans.

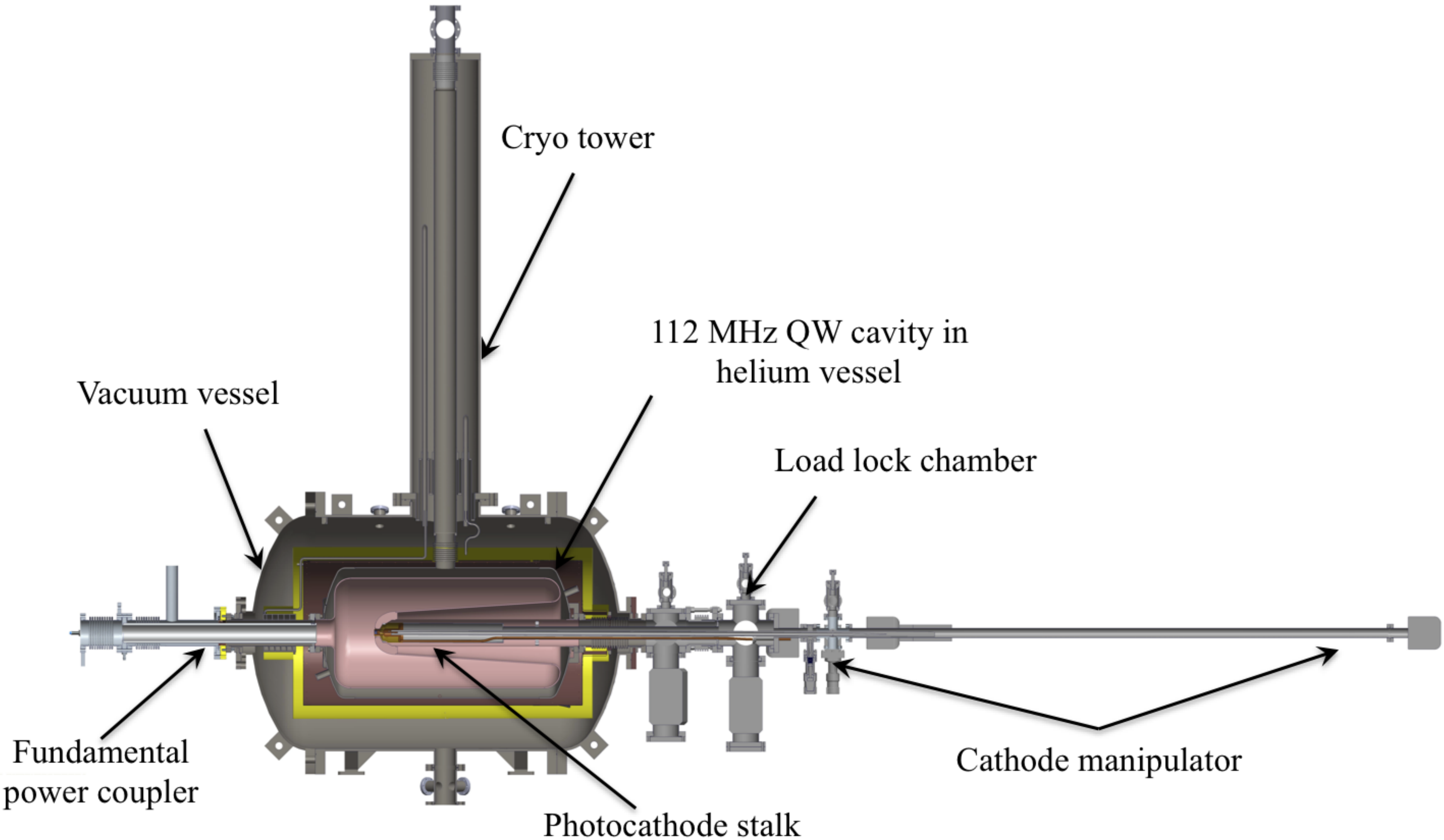
112 MHz SRF gun for CeC PoP experiment

- Superconducting 112 MHz QWR was developed by collaborative efforts of BNL and Niowave and will be used to generate electron bunches for CeC PoP (high charge, low rep. rate).
- Why 112 MHz?
  - ✧ Low frequency: long bunches – reduced space charge effect.
  - ✧ Short accelerating gap: accelerating field is almost constant.
  - ✧ Cathode does not have to be mechanically connected to SRF structure: flexibility in cathode types.

SRF gun parameters

RF frequency	112 MHz
Maximum energy gain	2.0 MeV
Bunch charge	1 to 5 nC
Bunch repetition frequency	78 kHz
R/Q	127.3 Ohm
Geometry factor	38.5 Ohm
Cavity Q_0 at 4.5 K	1.8e9
Cavity RF losses	17 W
RF losses in the cathode stalk	38 W
Frequency tuning range	78 kHz
Q_{ext}	1.25e7
Available RF power	2 kW
RF power amplifier	Solid State

112 MHz SRF gun cryomodule

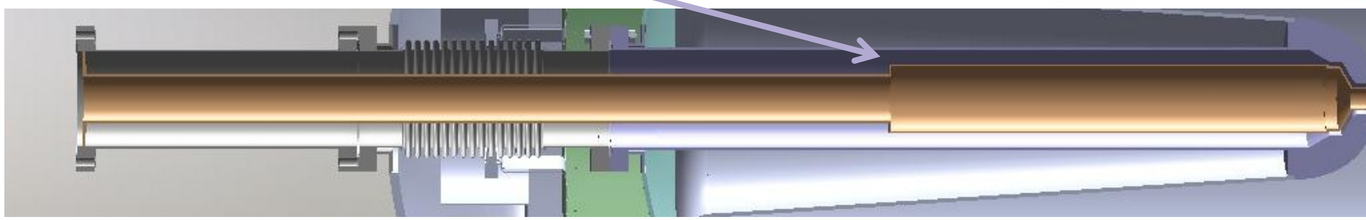


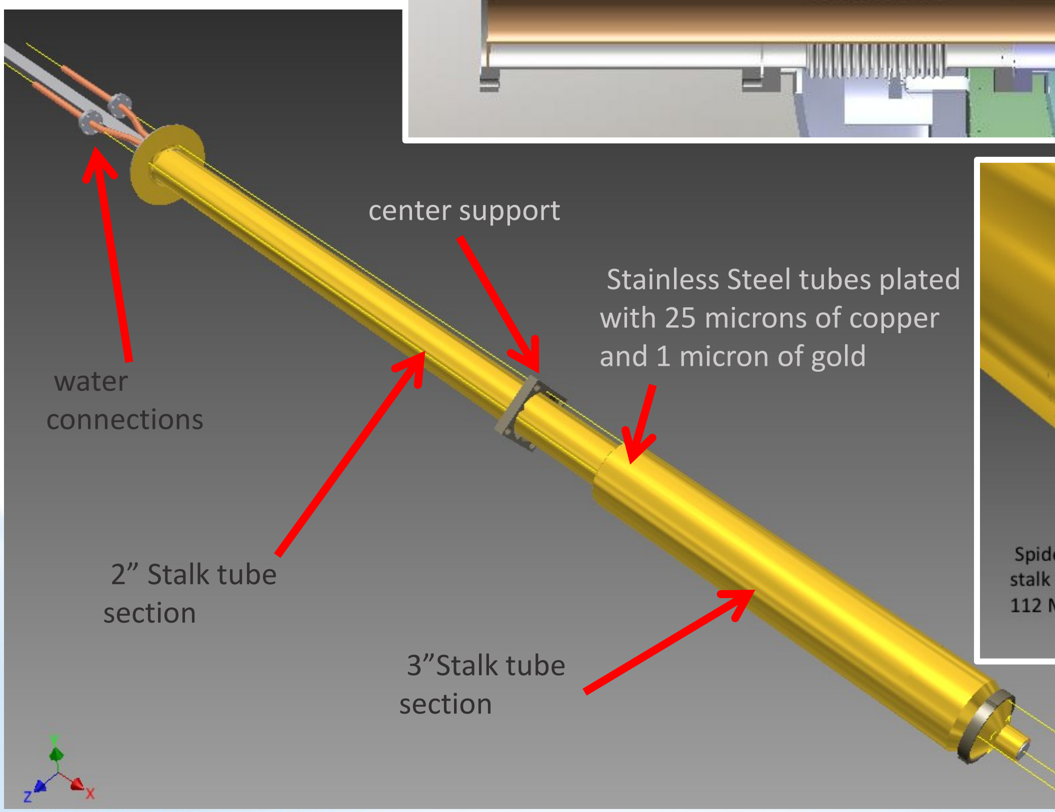
112 MHz SRF gun overview

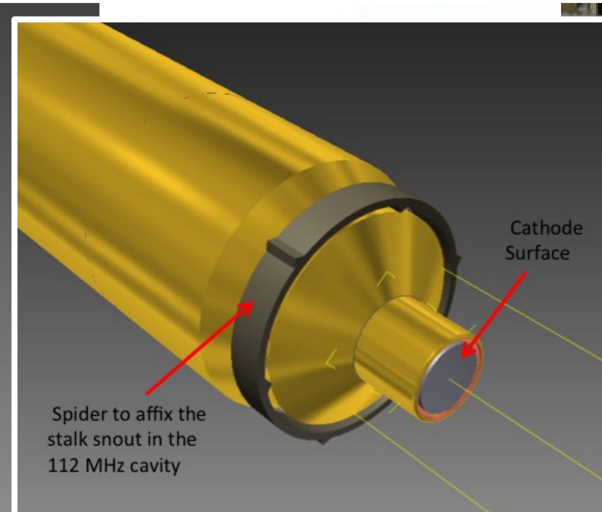
- Electron beam will be generated by illuminating a CsK_2Sb photocathode with a green (532 nm) light from a laser.
- The photocathode is located in a high electric field. Immediate acceleration of the electrons to a high energy reduces emittance degradation caused by a strong non-linear space-charge force. The low RF frequency of the gun reduces effect of RF curvature on the beam.
- The gun will produce electron beam with up to 5 nC charge per bunch, 78 kHz repetition frequency. The bunch train repetition rate is equal to the revolution frequency of ion bunches in RHIC thus allowing us to cool ion one bunch.
- A CsK_2Sb photocathode was chosen as it works with green light (more convenient than UV for some alternatives) and has much better life time than GaAs. A NaK_2Sb photocathode is under consideration.

Cathode stalk design

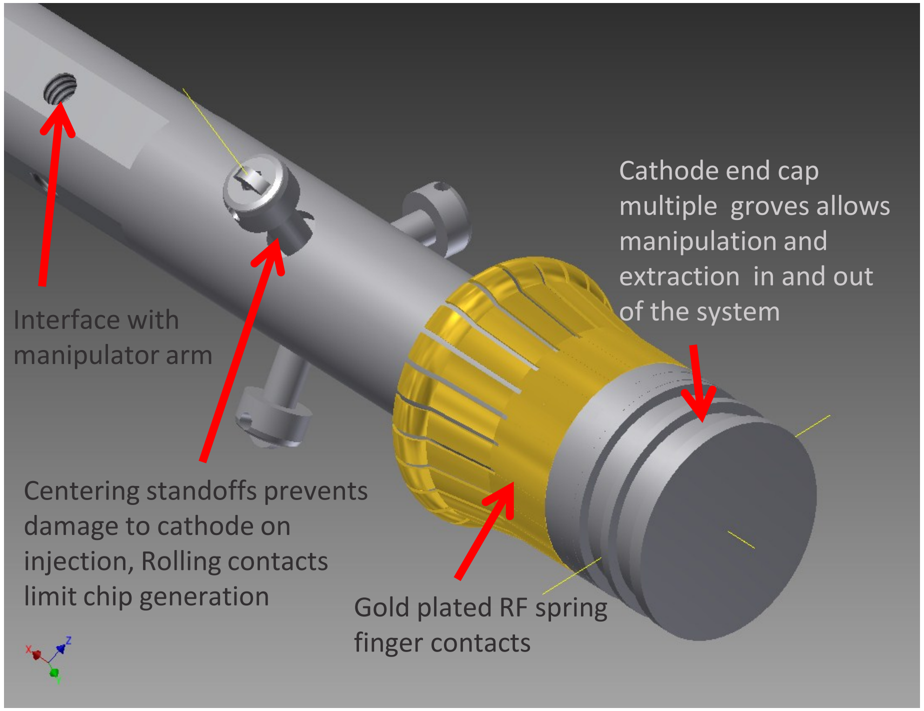
- The cathode stalk is a hollow center conductor of the coaxial line formed by the stalk and the cavity.
- The stalk is shorted at one end and is approximately half wavelength long. It will be permanently installed in the gun.
- A step at $\lambda/4$ from the short creates a quarter-wave impedance transformer and reduces RF losses in the stalk from ~65 W to ~25 W.
- The gold plating is aimed to reduce radiation heat load from the RT stalk to the cold (4.5 K) niobium.
- A small cathode puck is inserted inside the stalk and can be replaced when necessary with a new one.

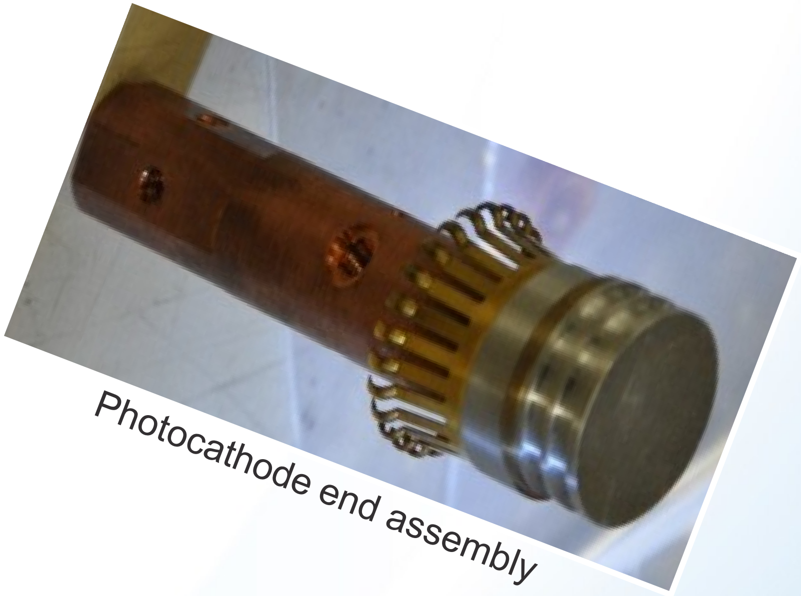




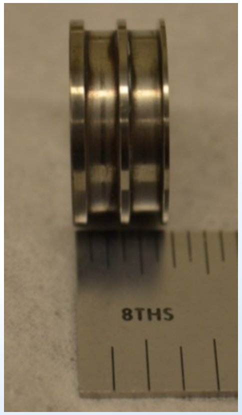


Cathode end assembly





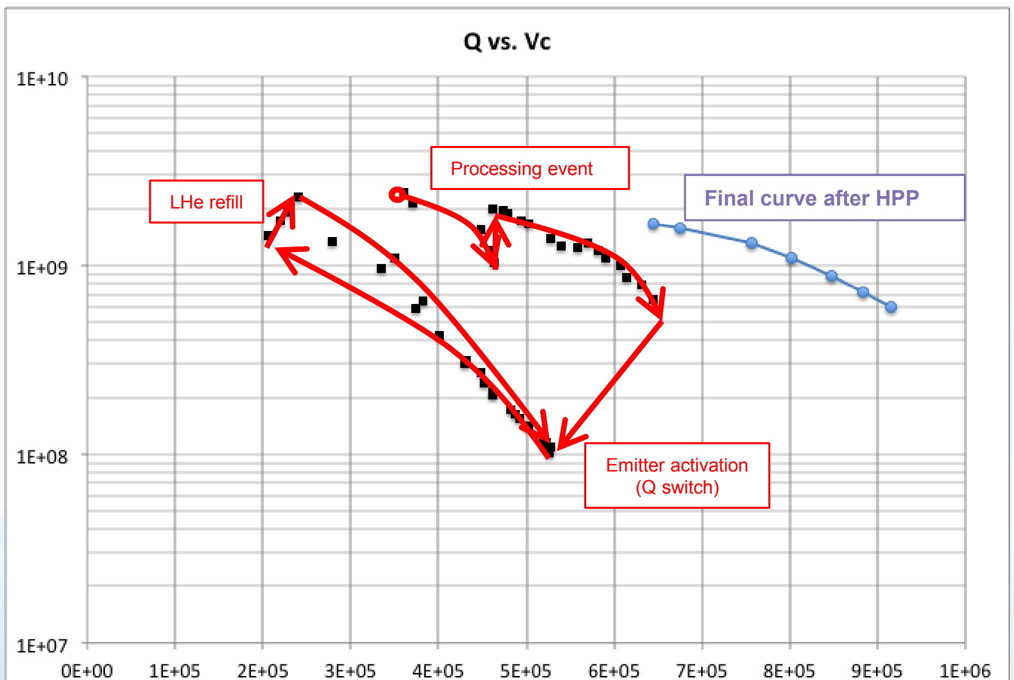
Photocathode end assembly



Cathode puck

SRF gun testing at Niowave

- A second cold test of the gun (in a new cryostat) was successfully completed at Niowave last February.
- The gun reached 0.92 MV, limited by insufficient radiation shielding at Niowave.
- With no radiation shielding issue in the RHIC tunnel we should be able to reach higher gun voltage.
- The gun is currently in the RHIC tunnel. All other systems are being installed.
- The commissioning will start in early 2014.



Summary

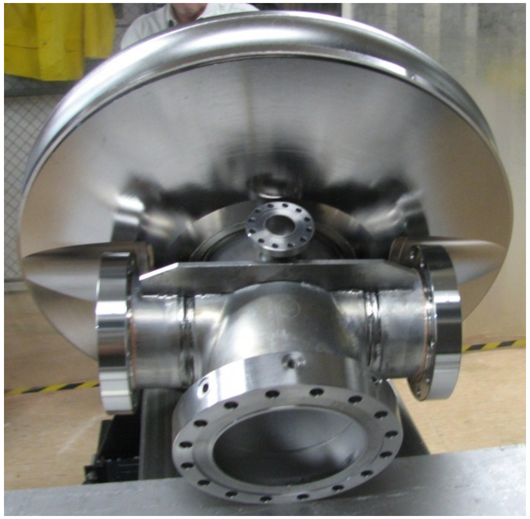
- Two SRF photoemission electron guns are in installation/commissioning stages at BNL.
- The 704 MHz SRF gun for R&D ERL has been commissioned w/o a cathode earlier this year.

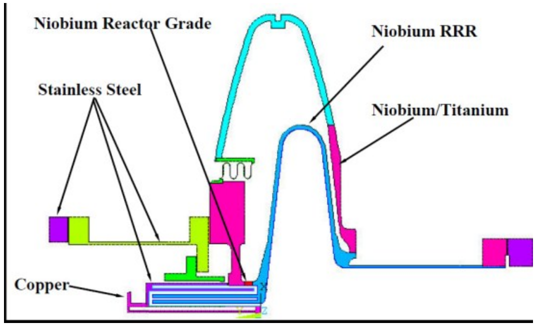
- The 112 MHz SRF gun cryomodule has been fabricated and tested up to 0.9 MV, limited by insufficient radiation shielding.
- It will be re-tested and conditioned to full voltage after installation in the RHIC tunnel is complete in early 2014.
- This will be followed by 2 MeV beam line commissioning.

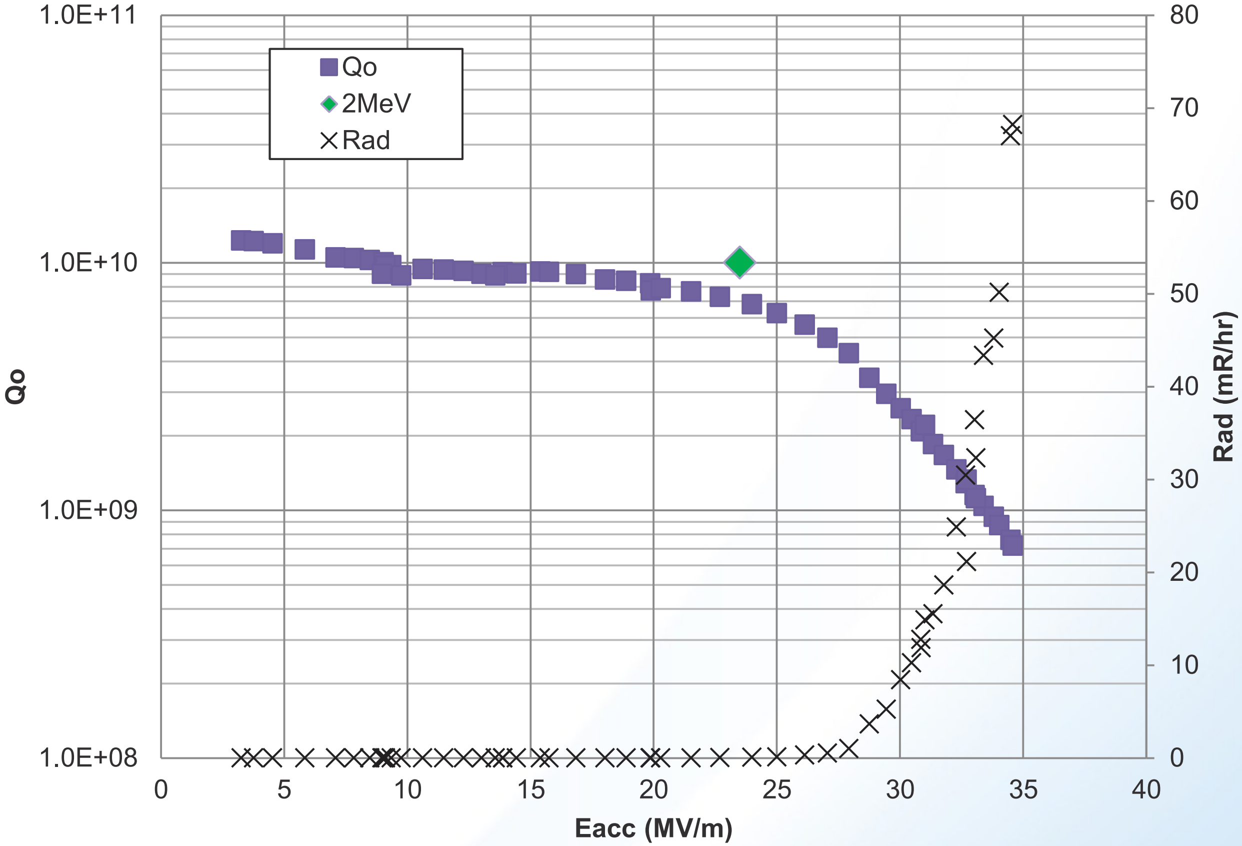
Thank you!

Backup slides

SRF gun cavity: Vertical test







- The cavity was tested vertically at JLab.
- It reached 2 MV (23 MV/m) with $Q_0 \sim 8 \times 10^9$ without a Nb cathode stalk.
- There was severe mulitpacting in the triangular-grooved choke-joint area with Nb cathode.
- In the SRF gun, the cathode stalk material is copper.